Detecting Extrasolar Terrestrial Planets in High Magnification Gravitational Microlensing Events

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ABSTRACT

Gravitational microlensing events of high magnification have been shown to be promising targets for searching for extrasolar planets. However, only a few events of high magnification have been detected using conventional survey techniques. Here we demonstrate that high magnification events can be readily detected in microlensing surveys using a strategy of high frequency sampling of target fields and real-time difference imaging analysis. We present 10 microlensing events with peak magnifications greater than 40 that were observed towards the Galactic Bulge during 2001 by MOA. We show that the efficiency for detecting Earth-mass planets in future events such as these is high if they are monitored intensively around the times of peak magnification. Such monitoring would yield a first measurement of the abundance of terrestrial planets in the Galaxy.

Subject headings: Gravitational lensing: microlensing—stars: planetary systems

1. Introduction

Precision radial velocity measurements of bright nearby stars now almost routinely detect gas-giant planets with orbital radii ranging from substantially less than that of Mercury to greater than that of Earth (Mayor & Queloz 1995; Marcy & Butler 1998). The reality of

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these planets was placed beyond doubt with the observations of transits of one of them across its host star (Charbonneau et al. 2000; Henry et al. 2000; Jha et al. 2000). Gravitational microlensing measurements are now producing complementary data on planets orbiting distant stars at larger orbital radii and, perhaps more significantly, with lower masses (Rhie et al. 2000; Albrow et al. 2001; Bond et al. 2001a).

The importance of well-aligned or high magnification microlensing events for detecting planetary companions to the lens star was first pointed out by Griest & Safizadeh (1998). They demonstrated that Jupiter-mass planets are readily detectable (if present) in events with maximum amplication, $A_{\rm max}$, as low as 10, and that Neptune-mass planets are detectable in events with $A_{\rm max} = 50$ if they are monitored intensely around their times of peak magnification. Unfortunately, the vast majority of the more than 1000 microlensing events that have now been detected by survey groups (Alcock et al. 2000; Derue et al. 2001; Bond et al. 2001b; Wozniak et al. 2001) were of low magnification. We are aware of only one event with high magnification that received intensive observational coverage at its peak. This event, MACHO 98–BLG–35, reached $A_{\rm max} \sim 80$. The observations yielded large exclusion regions for gas-giant planets surrounding the lens star, and also evidence for an Earth-mass planet near its Einstein ring (Rhie et al. 2000; Bond et al. 2001a). Two other events, OGLE 00–BUL–12 and MACHO 99–LMC–2, received less intensive coverage yet still yielded large exclusion regions for gas-giant planets (Bond et al. 2001a). Significant progress could clearly be made if one had a larger sample of high magnification events to work with.

2. Observations

During 2000–2001 a campaign of observations was undertaken by the MOA collaboration with the aim of improving the detection rate of high magnification events. A 0.6m telescope at the Mt John Observatory in New Zealand (170° E, 44° S) with a mosaic camera comprised of three 2k × 4k thinned CCDs was used. An area 17 deg^2 towards the Galactic Bulge that is relatively unobscured by dust was monitored. Images taken in 2000 were used to build a database of variable stars and to detect some microlensing events (Bond et al. 2001b). The observations in 2001 were made primarily to search for microlensing events and to provide real-time alerts to follow-up groups[6].

A total of 53 possible microlensing events were detected in real time in 2001, of which 10 had $A_{\rm max} > 40$. The details of these events are given in Table 1 and their light curves are shown in Fig. 1. We determined the parameters $A_{\rm max}$ and the the Einstein crossing time

[6]http://www.phys.canterbury.ac.nz/ physib/alert/alert.html

$t_{\rm E}$ by fitting the standard single lens microlensing profile given by Paczynski (1986). The constraints on these parameters were determined by a thorough examination over a range of values of $A_{\rm max}$ and $t_{\rm E}$. For some events only lower limits could be determined. Most of the events had $A_{\rm max} > 100$ and all stood out clearly as shown, for example, in Fig. 2. It is noteworthy that most of these events were observable for a few days only near their peaks. However, their Einstein crossing times were not unusually short. With the exception of event 5 (which was of unusually long duration), all events had $t_{\rm E}$ in the range 10–40 days indicating that the same population of lens stars was being probed in this survey as in previous surveys (Udalski et al. 2000).

The MOA survey differs from earlier ones (Alcock et al. 2000; Derue et al. 2001; Wozniak et al. 2001) in two ways. The sampling was repeated several times per night (up to six times) weather permitting, to enable very rapid events to be detected. Also, real-time difference imaging analysis was employed. This permitted events to be detected that would have otherwise been missed due to some combination of intrinsic faintness of the source and the degree of image crowding. With the exception of the first event, all the events in Table 1 are of this type. The new survey procedure evidently allowed us to tap into a huge reservoir of faint microlensing sources that had previously not been fully utilized. Indeed, the data in Table 1 imply the source stars for all the events except the first were sun-like when allowance is made for reddening caused by dust (Schlegel, Finkbeiner, & Davis 1998). These dwarf stars are ideal for planet hunting because source-size effects that tend to wash out planetary signals are minimised (Griest & Safizadeh 1998). Also, our simulations (see below) show that the effects of spots on these stars up to twenty times larger than those observed on the sun can be ignored.

3. Discussion

It is evident from the above that microlensing events of high magnification with sun-like sources can be readily detected. Griest & Safizadeh (1998) showed that moderately intensive monitoring of their peaks can provide information on the presence or absence of giant planets orbiting the lens star. We investigated the efficiency of low-mass planet detection in events of high magnification with solar-like sources that are monitored both frequently and accurately. We considered events monitored during the full-width-half-maximum, $t_{\rm FWHM}$, of their light curves. This time is given by $t_{\rm FWHM} = 3.5 t_{\rm E}/A_{\rm max}$ and is typically in the range 10–30 hours. Fig. 3 shows the perturbation produced by an Earth-mass planet near the Einstein ring for an event with $A_{\rm max} = 100$ over a range of position angles with respect to the source trajectory during $2t_{\rm FWHM}$. It is apparent that, in these events of higher magnification, planets of low mass may be detected, provided the light curve is sampled often enough and accurately enough. In practice, this means making measurements about every five minutes during $t_{\rm FWHM}$ with a precision of a few parts per thousand. This is achievable using 1-m class telescopes equipped with CCD detectors and analysing the data using difference imaging (Alard 2000; Wozniak 2000; Bond et al. 2001a). This procedure uses the vast amount of information that is contained in the dense stellar fields where microlensing occurs (Alard 2000; Wozniak 2000), and is assisted by the short time-span of the observations.

Fig. 4 shows the results of further simulations of light curves over a range of lensing system configurations. Simulated light curves, each comprised of 300 measurements taken during $t_{\rm FWHM}$, were computed for a 1-m class telescope observing in the I passband. We assumed a passband width of 200 nm, exposure and readout times of 200 s and 100 s respectively, and a combined throughput of 25% for the telescope and camera. We considered events with $A_{\rm max} = 50$, 100, and 200 that attained a peak I magnitude of 15. Nine events detected in 2001 were in this category. We assumed measurement accuracies two times larger than the photon statistical limit, consistent with typical measurement accuracies attained using the image subtraction technique and calculated the quantity $\Delta\chi^2 = \chi^2_{\rm single} - 300$. Here, $\chi^2_{\rm single}$ denotes the value derived by fitting the light curve for a single, planet-less lens to the simulated data for a lens with a planet. Adopting $\Delta\chi^2 > 60$ as a detection criterion, we identified zones of detectability lying around the Einstein ring as shown in Fig. 4. The $\Delta\chi^2 > 60$ requirement corresponds to <1% probability for statistical fluctuations causing a planet-like signal.

It is seen from Fig. 4 that Earth-mass planets can be detected with high efficiency for orbital projected radii in the range 0.7–1.5$r_{\rm E}$ or ∼1.3–2.9 AU in high magnification events that are monitored intensely during $t_{\rm FWHM}$. For events with $t_{\rm FWHM} \sim 24$ hours, a world-wide network of 1-m class telescopes is required to carry out the peak measurements, or alternatively one telescope at the Antarctic or in space. For more rapid events, fewer telescopes are required, but a commensurate increase in telescope aperture up to 2-m is required to achieve the sensitivity shown in Fig. 4.

In either case, follow-up measurements with the Hubble Space Telescope or a comparable telescope would be required to determine accurately the baseline intensity of a source star (Bennett et al. 2001). This information is required in order to determine the value of $A_{\rm max}$ accurately, and hence the planet:star mass ratio accurately for any detected planet. Further follow-up measurements a few years later with the Next Generation Space Telescope should enable the lens star in any event to be observed directly as it begins to diverge from the source star (Bond et al. 2001a). This would enable the absolute value of the mass of a planet to be determined, and also its absolute instantaneous projected radius at the time of the microlensing event.

4. Summary and Outlook

We have demonstrated that high magnification events can be readily detected in microlensing surveys with a strategy of high frequency sampling of survey fields and real-time difference imaging analysis, and that information on the presence of low-mass planets can be determined from brief but intensive follow-up observations. With a sufficient sample of well-monitored high magnification events, a measurement of the abundance of terrestrial planets would be possible. This would be biased towards planets orbiting stars with masses $\sim 0.3 M_{\odot}$ because most lens stars have such masses. It will also be biased towards planets at projected radii $\sim$1.9 AU, the typical value of $r_{\rm E}$. Such planets will lie on the extremities of the habitable region (Kasting, Whitmire, & Reynolds 1993; Wetherill 1996; Des Marias & Walter 1999; Gonzales, Brownlee, & Ward 2001). Consequently, the abundance of habitable planets would only be marginally probed. Nevertheless, an initial benchmark for the abundance of terrestrial planets should be achievable.

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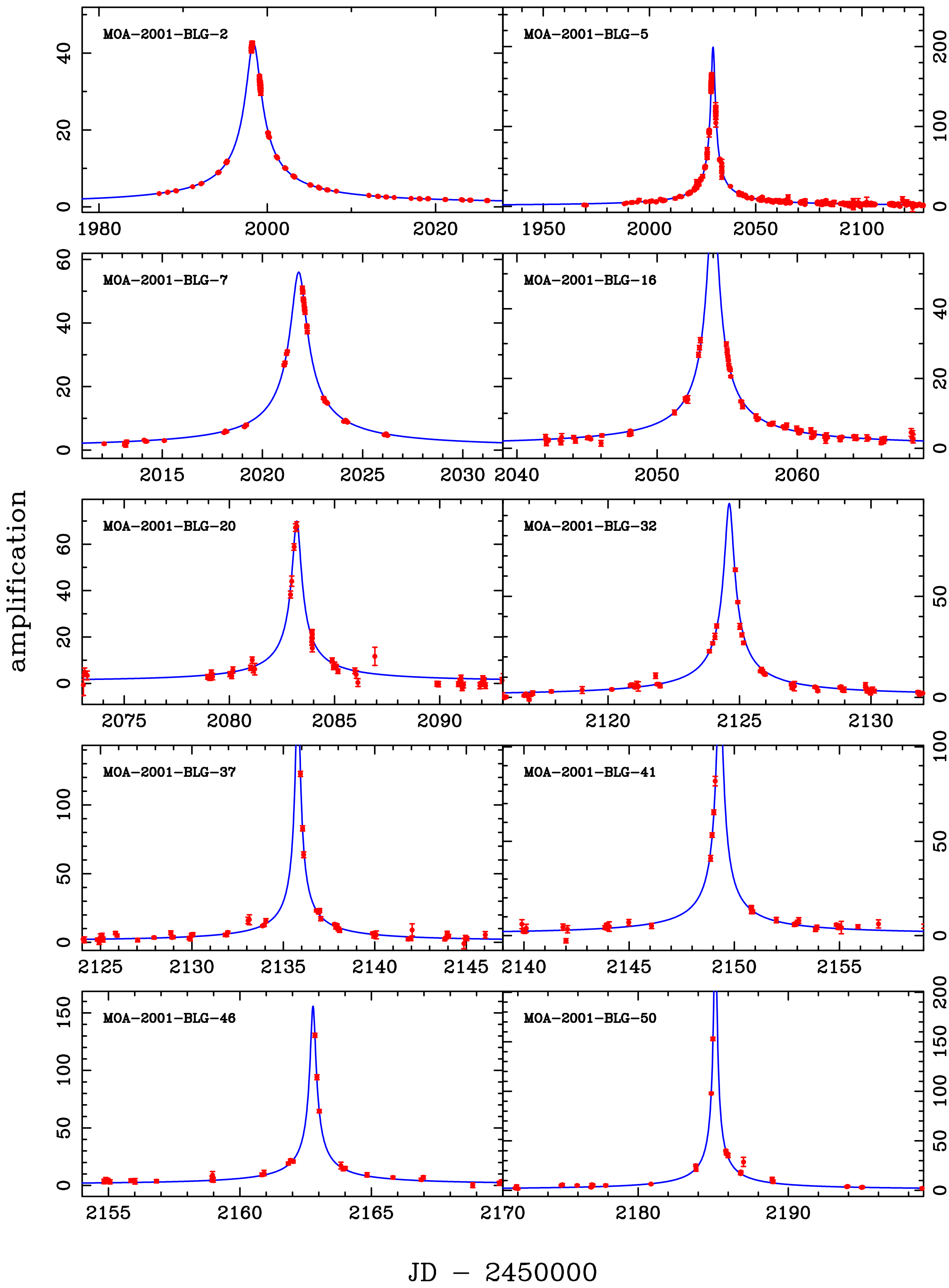

Fig. 1.— Light curves of high magnification microlensing events detected by MOA during 2001. The photometric flux measurements have been converted to amplifications using the fitted microlensing parameters given in Table 1

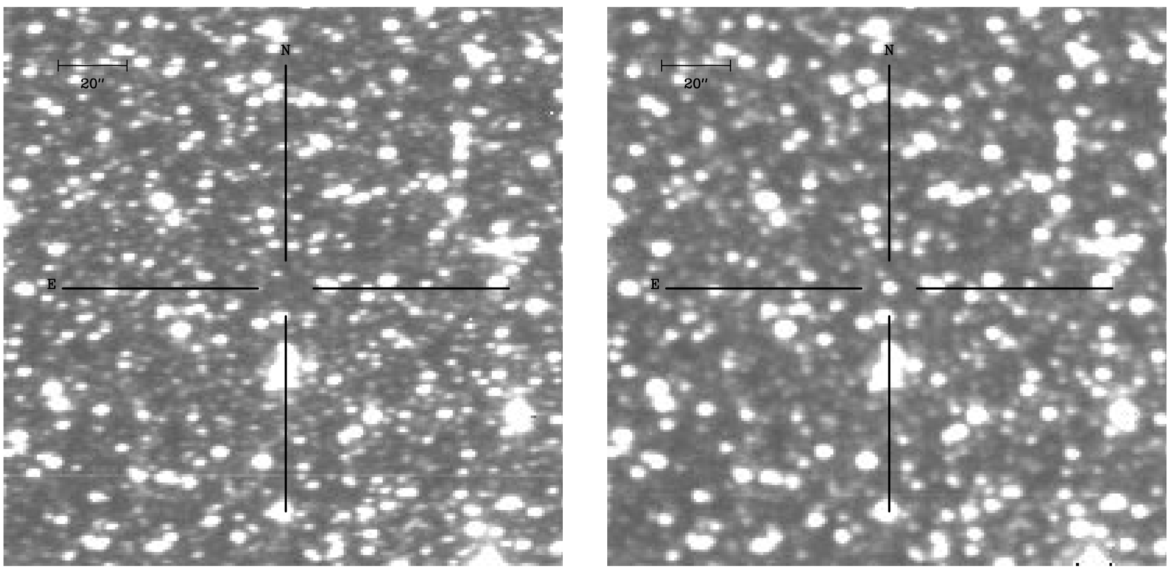

Fig. 2.— Sample images of event MOA 01–BLG–5 taken when the event was at its baseline (left) and near its peak (right). The event stood out clearly near its peak, but was invisible with the MOA telescope at its baseline.

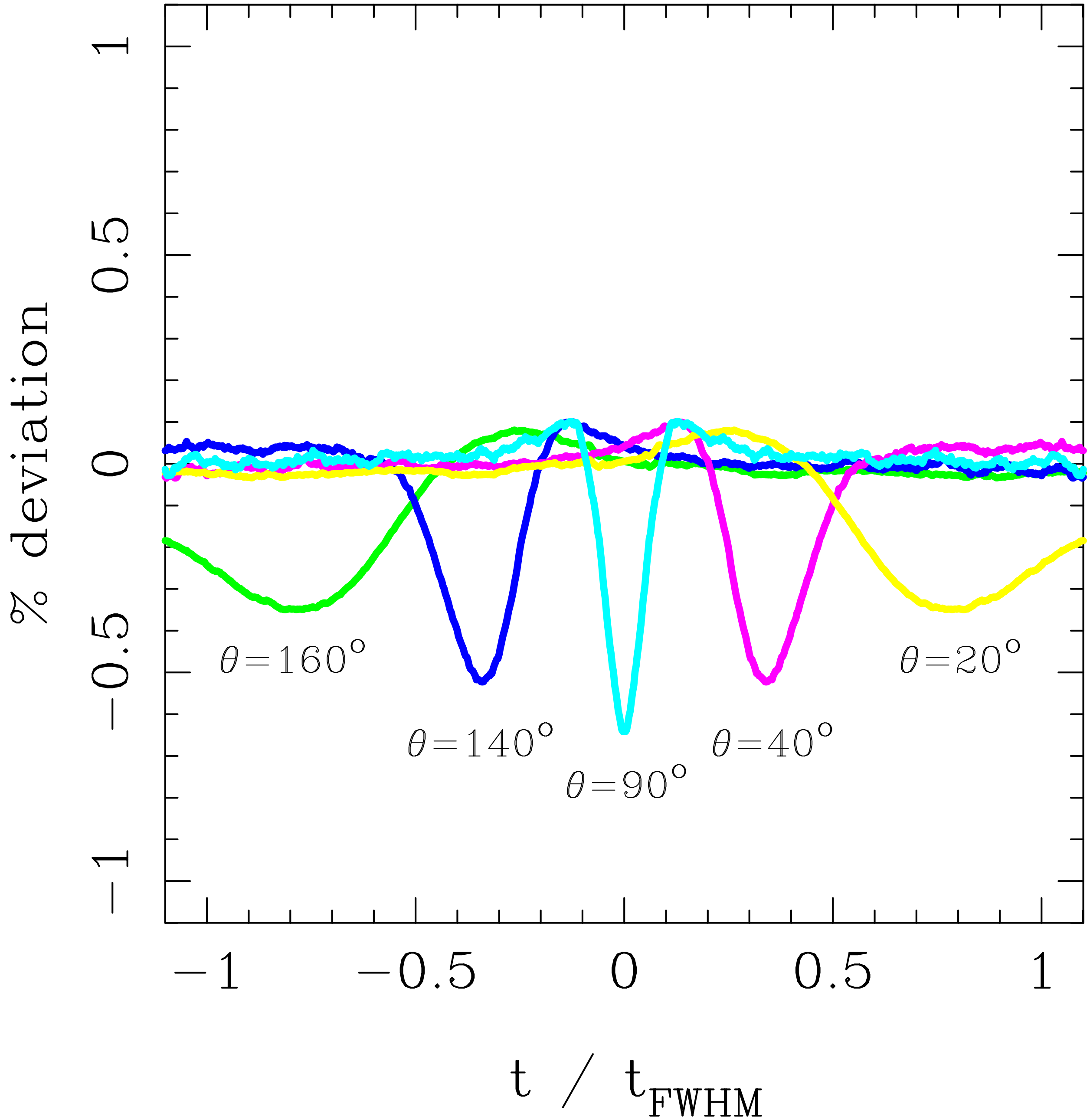

Fig. 3.— Perturbations in the light curve due to a planet orbiting the lens star in a microlensing event of peak amplification of 100. The percentage deviation is that from a single lens profile. The planet:star mass ratio is 10^{-5} which corresponds to an Earth mass planet orbiting a $0.3M_{\odot}$ star. The projected orbital radius at the time of the microlensing event is $0.8r_{\rm E}$, i.e. $\sim$1.5 AU. The source star radius is $R_{\odot}$. The position angle, θ, is the angle between the track of the source star and the star:planet line. For position angles between 180° and 360° the perturbations are the positive mirror images of those shown above. Heavier planets produce larger perturbations, and planets closer to the Einstein ring produce both larger and sharper perturbations. Hence the position angle, mass ratio, and instantaneous projected orbital radius of a planet can be determined from the perturbations.

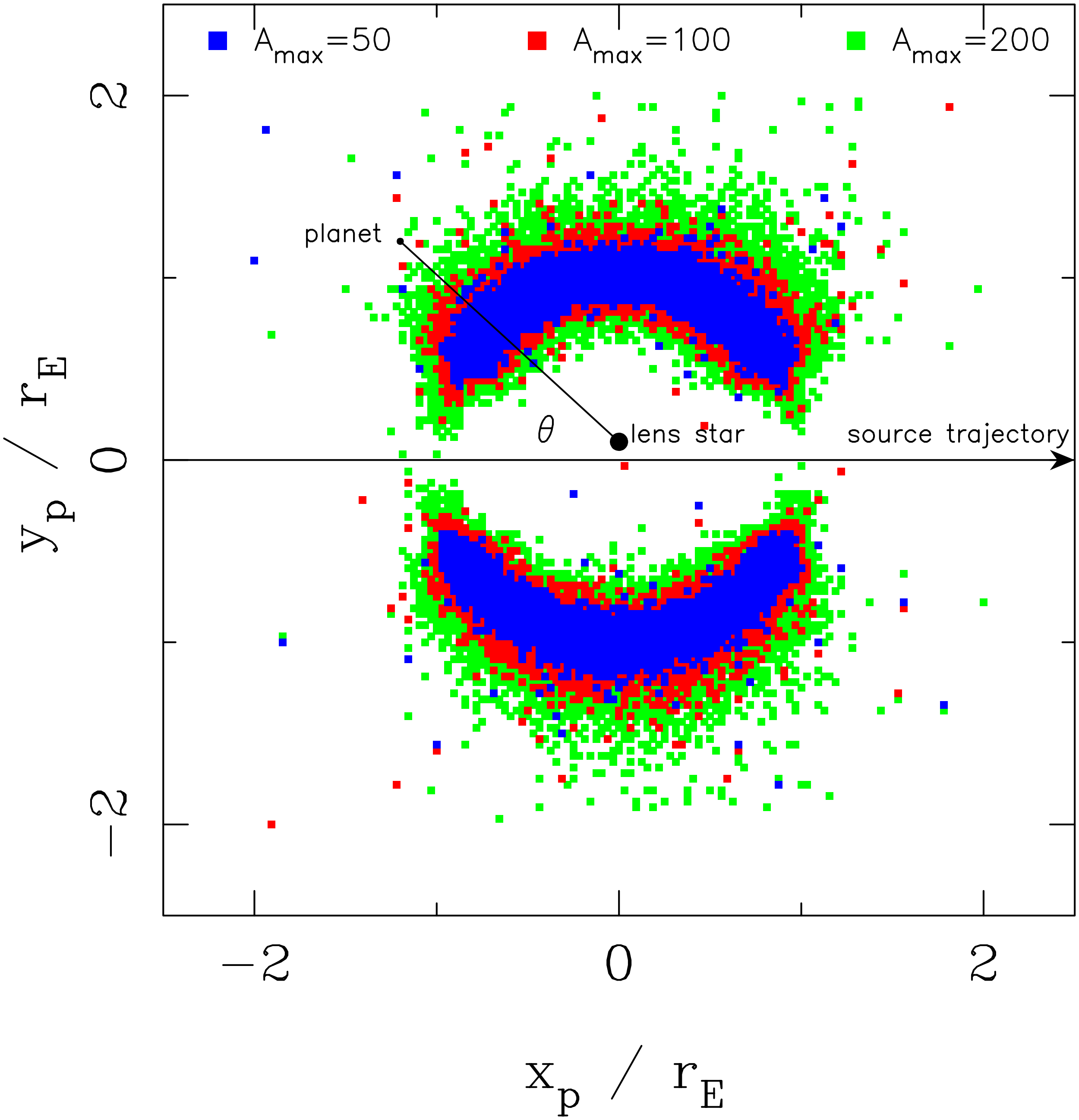

Fig. 4.— Detectability zones in the lens plane for an Earth-mass planet orbiting a $0.3M_\odot$ star in microlensing events with peak magnifications of 50, 100, and 200. The units for both axes are in $r_{\rm E}$ which is typically ~ 1.9 AU. In this coordinate system, the lens star is located at position (0, u_0), where u_0 is the impact parameter, which is $\sim 1/A_{\rm max}$. The vertical position of the lens star is exaggerated in the figure. If the projected position of the planet falls in the shaded regions at the time of the microlensing event, then it is detectable at the 99% confidence level if intensive photometric monitoring of the microlensing event is carried out during the time interval $t_{\rm FWHM}$. The angular diameter of the zone of detectability is <1 mas.

Table 1. Details of high magnification events detected in 2001

Event[a]	R.A. (J200.0)	Dec. (J2000.0)	$I_{\max}$	$A_{\max}$	t_{E} (days)	t_{FWHM} (hours)
2	17 55 09.1	−28 44 59.4	11.6	$42.6\pm^{1.1}_{1.0}$	$38.2\pm^{0.7}_{0.7}$	74.6
5	18 16 42.9	−23 24 19.6	14.3	$200\pm^{124}_{46}$	$194\pm^{17}_{46}$	80.7
7	18 08 58.8	−27 36 11.9	14.6	$56\pm^{17}_{11}$	$22.0\pm^{5.8}_{4.0}$	32.7
16	18 11 50.8	−27 33 28.6	<14.1	>73	$28.6\pm^{3.8}_{9.4}$	<32.6
20	18 06 50.7	−27 15 13.3	16.2	$70\pm^{326}_{40}$	$14.9\pm^{64.5}_{8.0}$	17.7
32	18 03 35.2	−29 52 20.8	<14.1	>96	$17.6\pm^{11.5}_{5.7}$	<15.3
37	17 55 23.4	−28 56 44.2	<14.5	>186	>23.8	~10.6
41	18 07 13.4	−25 25 18.3	<14.5	>137	>20.6	~12.5
46	17 57 48.9	−29 36 35.5	14.6	$156\pm^{320}_{82}$	$16.9\pm^{33.5}_{8.7}$	9.1
50	17 56 33.0	−28 54 19.5	<14.2	>289	>31.7	~9.1

[a]The event number corresponds to that in the discovery sequence of all microlensing events found by MOA during 2001

Note. — The event parameters were derived by fitting a single lens microlensing profile to the data. The peak I magnitude was derived from the fitted baseline flux and the peak amplification. The fluxes were calibrated to I band values using UBVRI photometry of nearby stars (Paczynski et al. 1999). The limits are at the 95% confidence level or higher (Bond et al. 2001b).